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Approaching ITER PF Coil Manufacturing

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***Abstract*—The ITER poloidal field (PF) coil system provides a magnetic field for plasma shaping and position control together with the central solenoid coils; it needs to operate in a fast pulse mode, leading to induced voltages of up to 14 kV on the coil terminals during operation. The PF magnet system consists of six coils. The cable-in-conduit conductors with niobium-titanium (NbTi) superconducting material are used in the coils. All coils are fabricated by stacking six to nine double pancakes wound by two-in-hand winding scheme. The six PF coils (PF1 to PF6) are attached to the toroidal field coil cases through the flexible plates or sliding supports to allow small radial and vertical displacements. The PF coils will be procured by the European and Russian domestic agencies under separate procurement arrangements. To accelerate the PF6 coil schedule, which is one of the critical paths for the ITER schedule, a cooperation agreement has been placed between F4E and ASIPP in China in October 2013 with the CN-DA support. Before starting the manufacturing of the coil, the component qualification has been started, such as the 3 × 3 conductor mock-up, turn insulation, and helium inlet with the dummy conductors. Corresponding mechanical and electric tests were carried out at room temperature and 77 K. The PF dummy double pancake is also wound to demonstrate the winding. This paper presents the updated design for manufacturing of components. Their fabrication methods are also described. This paper concludes with a summary state report on PF1 dummy winding.**

***Index Terms*—Fusion, ITER, PF coil, superconductor.**

I. Introduction

THE ITER Poloidal Field (PF) magnet system consists of six circular coils procured by the European and Russian domestic agencies under separate procurement arrangements (PA). The outer diameters of the coils vary between 8 and 24 m. For the superconducting property, the PF coils use Niobium-Titanium (NbTi) superconducting conductor. The main roles of the PF coil are providing the position equilibrium of plasma current (i.e. the fields to confine the plasma pressure) and the plasma vertical stability [2].

All coils consists of stacking 6 to 9 double-pancake (DP) windings wound with NbTi superconducting cable-in-conduit conductors (CICC) by two-in-hand winding scheme. Several coil components were updated after the final design review held in 2009 and finally the designs of most critical components were determined in 2014. From 2014, each DA has started the preparation of component qualification and real qualification tests.

Regarding the PF2-5 coils, six independent contracts for the fabrication of the PF2-5 coils have been being placed with the European Domestic Agency (EUDA). To accelerate the PF6 coil schedule, which is one of the critical paths for the ITER schedule, a manufacturing cooperation agreement between EUDA and the Institute of Plasma Physics Chinese Academy of Sciences (ASIPP) in China was put in place in October 2013 with the support of the CN-DA. The PF6 building construction and test were completed and the preparation activities for the tooling and component qualifications are underway at ASIPP.

For the PF1 coil fabrication, the Russian Federation Domestic Agency (RFDA) has completed the activities on the building and tooling preparation in 2014 and as part of the qualification activity, the component qualification has been started in 2014. As a first step, several qualification samples such as helium inlet sample, a mock-up with 3 × 3 dummy conductors and the turn insulation samples with resin were fabricated. Mechanical and electrical testing of the samples was carried out at room temperature and 77 K. The winding facilities are being procured in Russian Federation and the Dummy Double Pancake was wound in 2015.

This paper focuses on the qualification activities which include the requirements, the sample preparation, test method and the acceptance criteria. Finally the paper concludes with a summary of the result of the component qualification tests and dummy double pancake winding [3].

II. Requirement for Component Qualification

To meet the expected schedule of PF1 coil, RFDA requested IO to start the PF1 dummy pancake winding in the middle of 2015. To solve the schedule issue of the PF1 dummy double pancake winding, ITER and RFDA have selected three imperative components qualification activities which include Helium inlet qualification, Turn insulation qualification, 3 × 3 mock-up qualification.

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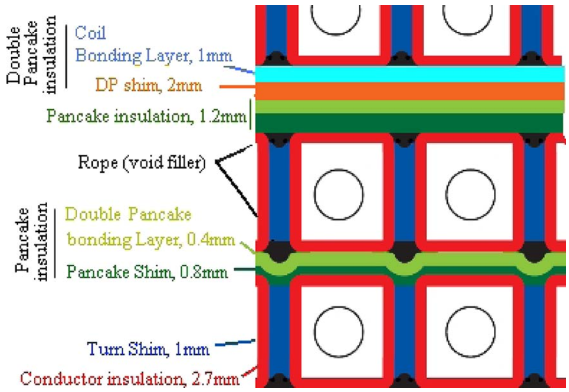

Fig. 1. PF coil insulation system.

A. Helium(He) Inlet

Each double pancake is supplied with supercritical helium (4.2 K and ~0.6 MPa in normal operation) at the inner diameter of the coil through a coolant inlet pipe located at the mid-length of each conductor in the double pancake [4]. As a preliminary qualification, two types of samples (the straight type and the curved type) should be prepared with the following procedures.

The slot is machined in the conduit with a machining tool. The thermocouples are planted in at least 4 places under the weld since the thermocouple joint is under the weld in the point of the highest probable temperature during welding. Since during welding process, heat flux into the NbTi-strands could cause a degradation of the critical current, the welding should be carried out below (250 °C for NbTi). After completion of the weld, the samples should be leak-tested at room temperature and 5-time cool down cycles at 77 K and the leak test is repeated. The various welding tests such as visual, X-ray and microscopic examinations should be carried out for the straight sample.

The fatigue test at 77 K is carried out in accordance with the ASTM standard E739-91. The tests demonstrate that the fatigue strength of the conduit with the welded inlet is sufficient to last the lifetime of the PF Coils. The conductor jacket should withstand a cyclic longitudinal total strain range of 7×10^{-4} with the minimum value defined as 10% of the total range (strain ratio $R = 0.1$) during 600 000 cycles, or cyclic longitudinal total strain range of 14×10^{-4} with the minimum value defined as 10% of the total range ($R = 0.1$) during 30 000 cycles. And finally the leak test is performed after the fatigue test.

B. Turn Insulation Sample for Mechanical Test

All electrical insulation applied to ITER PF coil windings is formed by a multi-layer sandwich double barrier system manufactured by wrapping glass-polyimide tapes impregnated with epoxy resin [5]. The insulation of the conductor, DP and ground insulation is given in the Fig. 1. The turn insulation layer includes two layers of half overlapped interleaved polyimide film and dry glass. The necessary turn insulation samples should be manufactured using the identical procedure foreseen for the manufacture and impregnation of the ITER coil insulation. For qualifying the mechanical properties of the insulation, the following types of tests are performed:

a) Tensile strength tests in 0° and 90° direction with respect to the wrapping direction.
b) Short-beam-shear test (3-point bending test).
c) Bonding to the steel test.

All samples are tested at 77 K in static load condition. The fatigue tests (for the tensile sample and the bonding to steel samples) up to 10^5 cycles are performed. The maximum loads are varied, while the minimum load is kept constant at 10% of the ultimate tensile strength. The fatigue life curve is plotted using a fit to the lowest measured values and the intercept with the 30 000 cycle line is used to determine the strength. At least 10 valid measurements per point are available. This test condition is representative for the coil operation. In the case of the bonding to the steel, it should be qualified by testing the shear/compression bonding strength at 45°.

C. 3 × 3 Mock-up Sample

On the basis of PF coil insulation system shown in Fig. 1, a single long mock-up is made from a stacking of 3 × 3 conductors to perform the electrical test and visual examinations of the insulation at 77 K. A bundle of 3 × 3 1.6-m long hollow square stainless steel profiles is insulated and impregnated with the materials foreseen for the ITER coil insulation. The fabrication sequence is representative for the manufacture of the ITER coil, i.e., (i) cleaning and sandblasting of the surface, (ii) insulating with dry glass-polyimide tapes and bundling the 9 bars, (iii) application of the ground insulation, (iv) impregnation with the foreseen resin and (vi) application of a metal screen on the surface.

Visual inspection after insulation is carried out for cracks, dry spots and other defects. The samples are subjected to cooldown to LN2 temperature (77 K) and warm-up a minimum 5 times to inspect the stack for cracks, dry spots and other defects. The photographs with ×50 augmentations of the stack and possible defects are taken and voids, cracks, dry areas or any other possible defect are not allowed. The sample is put in the Liquid Nitrogen bath immediately and warmed up naturally. It is much more severe condition compared to real PF coil operation. The High voltage (HV) tests which include AC, DC and Paschen tests are carried out to check the quality of the insulation.

D. Dummy Double Pancake (DP) Winding

The winding operation verifies the settings and controls of the winder for achieving the desired radius of curvature in the pancake and establishes the process of making the joggles in the pancakes and transitions between the pancakes. In-line conductor cleaning and insulation are established and synchronized. The winding basic criteria chosen for the execution of the DP is to wind the 1st layer (lower layer) from the outer to the inner side, and the 2nd layer (upper layer) from the inner to the outer side. The turn insulation is performed on the conductor using insulation wrapping heads integrated into the winding line. Wrapping speed is to be synchronized with the winding table speed. The layer and the tension of the insulation wrap (glass and kapton) are closely controlled.

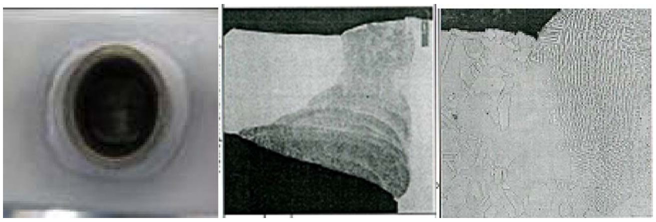

Fig. 2. (Left) Penetration test and (center) macro and (right) micro test of the He inlet weld.

Fig. 3. (Left) He inlet fatigue test sample and (right) He inlet sample cooldown.

III. Component Qualification Test

A. Helium (He) Inlet

The slot is machined in the conduit with a special machining tool and this tool could eliminate any visible damage to the superconducting strands. The region where machining is performed is carefully sealed and dust; particles and chips are continuously collected and removed. To plant the thermocouples, the holes are drilled from the sides and from the bottoms and it is demonstrated that the holes from the side could give the most reliable result for the temperature checking. The thermocouples are connected to the thermocouple reading. The welding parameters and procedures are established to maintain the temperature below the allowed (250 °C for NbTi) and there are 4 welding passes to control the temperature. After completion of the weld, the helium pressure inside the sample is pressurized with P $\geq$ 3 MPa to carry out leak test. There is no leak indication at a level of sensitivity of 1×10^{-9} Pa $\cdot$ m^3/s. After the leak test, the samples experience 5 cool down cycles between 77 K and room temperature. The leak test is repeated and there is no leak indication.

In the case of the curved type of He inlet sample, the inlet welds are achieved with full penetration in visual, X-ray and microscopic examinations, including destructive tests with desectioning several (3–4 minimum) cross sections of the conduit as seen in Fig. 2. There is no indication of defects in the welds of He inlet. In the case of the straight type of He inlet, as seen in the Fig. 3, the fatigue tests at 77 K are carried out. The tests demonstrate that the fatigue strength of the conduit with the welded inlet is sufficient to last the lifetime of the PF Coils. Finally, the sample is leak tested and there is no leak indication at a level of sensitivity of 1×10^{-9} Pa $\cdot$ m^3/s after 30 000 cycles.

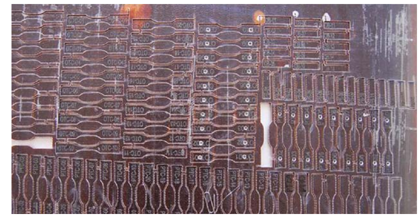

Fig. 4. Turn insulation qualification sample for tensile test and short beam shear test.

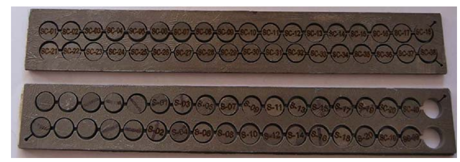

Fig. 5. Turn insulation qualification sample for the bonding to the steel test.

TABLE I
Mechanical Test of the PF1 Insulation Samples Results (MPa)

Type of testing	Static loading	After 30K cycles
Ultimate tensile strength (0°)	783 (750*)	220<Sf,N <282 (200*)
Ultimate tensile strength (90°)	425 (350*)	128<Sf,N<218 (125*)
3-point bending (0°)	90 (80*)	-
3-point bending (90°)	69 (55*)	-
Shear/compression strength	125 (150*)	91 (85)

*Criteria

B. Turn Insulation Sample for Mechanical Test

Figs. 4 and 5 show the sample for turn insulation qualification. For the tensile test sample and the short beam shear test sample, the turn insulation is performed on the stainless steel 316L plate (6 mm $\times$ 500 mm $\times$ 280 mm) with polyimide tape (32 mm $\times$ 0.05 mm) and fiber glass tape (40 mm $\times$ 0.25 mm). For the bonding to the steel test sample, six fiberglass tapes (6 $\times$ 400 mm $\times$ 40 mm $\times$ 0.25 mm) are planted between two stainless steel 316L plates (2 $\times$ 390 mm $\times$ 45 mm $\times$ 3.5 mm) and then the samples are cut from plates manufactured by a vacuum-pressure impregnation process of laminated plates. All samples are tested at 77 K condition and the results of the tests are shown in Table I. It shows that all the results satisfied the criteria except the shear/compression strength test result in static loading conditions. Even though the shear/compression strength value could not reach the criteria, considering the design margin of the insulation, it is calculated that it is acceptable value.

C. 3 $\times$ 3 Mock-Up Sample

Fig. 6 shows a bundle of 3 $\times$ 3 conductors with 1.6-m long sample. The real fabrication sequence is (i) applying conductor insulation on 9 straight bars, (ii) applying turn shim, roving and pancake insulation on 3 $\times$ 2 stack (iii) applying turn shim, roving and pancake insulation on 3 $\times$ 1 stack (iv) applying double pancake insulation on 3 $\times$ 3 stack and impregnation with the foreseen resin and (v) application of a metal screen on the surface. There is no indication of cracks, dry spots and other defects after the impregnation.

Fig. 6. (Left) 3 × 3 mock-up sample and (right) cooldown test.

The sample was tested at full range of the high voltage modes at room temperature and at 77 K. The thermo-cycling is carried out 5 times between 77 K and room temperature and there are no visible changes or defects of insulation after thermo-cycling. There is no breakdown of the insulation or overlap on the surface during these tests. At DC modes, the leak current is much less than the criteria. At AC mode, some current which is greater than acceptable current is detected but it is confirmed that this current is generated by capacitive impedance in the sample. During the Pashen test, it is detected that there are some breakdowns on the external tubes and the tubes are repaired. After repairing the pipe insulation, the Pashen test results show that there is no breakdown of the insulation during the test.

IV. PF1 Dummy DP Winding

PF1 dummy DP winding started in December 2014 and the 1st layer of winding was completed in March 2015. It is agreed between ITER and RFDA that the 1st layer winding was carried out as R&D purpose for the 2nd layer winding. During the 1st layer, some issues are identified such as cleaning, irregular sandblasting, conductor surface roughness and insulation skim. Before starting the 2nd layer winding the issues are mostly identified and investigated. The main improvement is as follows.

To improve the homogeneity of the sandblasting, the pre-screening system is installed in the container to control the size of sand and it is possible to control the size of the sand between 0.1∼0.6 mm. It was discovered that the moisture could cause the irregular sandblasting. To remove the moisture in the sand, a moisture drying system is introduced to the sandblasting machine. By adding the drying system, it could prevent the blockage of sand in the tube of the sand blasting machine and it provides homogeneity of sand blasting.

To improve the cleaning of the conductor, the automatic chemical pre-cleaning unit is installed after the sandblasting unit. In addition to this automatic cleaning process, the conductor surface is cleaned manually every 7 meters when the taping machine stops to change the insulation tapes. And the surface roughness is checked every 7 m and it is controlled based on acceptance criteria $(3\sim 4\ \mu\mathrm{m})$. Since some scratches on the top surface of the conductor after the bending procedure were observed, the long guiding roller, which can prevent vertical movement (deviation) of conductor, is installed with the bending unit.

Fig. 7. PF1 dummy DP winding.

To determine the optimum condition of the turn insulation taping, it is determined to use 32-mm kapton tape. The optimum condition of overlapping is determined and the thickness of turn shim is determined. The compression of the turn insulation is done by the force of 2.6∼2.8 kN. The measurements of the turn position on the table are carried out by a 3D laser scanner.

As shown in Fig. 7, based on improvement of the winding process, the 2nd layer winding was completed successfully. The maximum winding speed is 1 turns/day. This double pancake will be impregnated as a subsequent step.

V. Conclusion

As a preliminary step of manufacture of PF coils, the several component qualifications and the dummy double pancake winding are carried out successfully. It is found that the measurement of during winding is very important. The bending of layer transition part and turn transition part requires high technology. The synchronization of taping is also important.

Several various component qualifications for PF1 coil such as joint and tail are well underway and EUDA is preparing the component qualifications for PF2-6 coils. After completion of these qualifications, PF coil real fabrication can start confidently.

VI. Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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